# THE FAULT IN OUR STARS

## Satellite swarms are threatening the night sky. Is low-Earth orbit the next great crucible of environmental conflict?

*By* **Joshua Sokol**

On 19 December 2019, Tony Tyson, an experimental physicist at the University of California (UC), Davis, joined a conference call with billionaire Elon Musk that helped shape the fate of starry nights on Earth.

The call was cordial but tense. Seven months earlier, Musk's company SpaceX had livestreamed a feed of 60 satellites drifting off into space from the bay of one of the firm's rockets. The satellites, the triumphant first wave of a project called Starlink, were built to beam down broadband internet to every corner of the globe. But as the satellites began to do laps around Earth, people looking up at night saw a string of glinting pearls as bright as the stars in the Big Dipper.

The first flotilla of 60 Starlink satellites was released in May 2019 from a SpaceX rocket.

Those five dozen satellites were just the beginning. Starlink already had permission to launch 12,000 satellites, roughly six times the number of active satellites then in orbit. The next year, the company added another 30,000. Other billionaire-backed companies—Jeff Bezos's Project Kuiper, and OneWeb, funded in part by Richard Branson—were planning comparable space internet swarms, leading to industry forecasts of more than 100,000 satellites in orbit by the end of the 2020s. In the best stargazing conditions, human eyes can perceive about 3000 twinkling stars overhead; if the planned satellites ended up as bright as the first Starlinks, they would fill future summer nights with a comparable number of creeping dots.

Almost overnight, a new arena of environmental conflict opened up. Astronomers



PHOTOS: (TOP TO BOTTOM) © MATT DIETERICH; SPACEX

In August 2020, Starlink satellite tracks were seen next to comet NEOWISE at Idaho's Craters of the Moon, a national monument. Fifty time-lapse shots, each 4 seconds long, were stacked to make the image.

weren't the only ones who saw an existential threat. Environmentalists, amateur stargazers, and Indigenous leaders working to revive astronomical traditions saw an affront to the planet's dwindling dark skies, an act as vandalistic as carving initials into a tree trunk—in front of the whole world. "From a cultural point of view, it is a desecration," says Rangi Mātāmua, a Māori cultural astronomer at Massey University, Manawatū.

For Tyson, the stakes were narrower and more personal—but no less dire. In 1996, when he worked at Bell Labs, he conceived a wide-field telescope capable of soaking in the entire sky overhead out to the edge of the visible universe every single night. That endeavor became a $700 million project supported by the National Science Foundation (NSF), one that would push charge-coupled device (CCD) cameras—a Nobel Prize–winning technology invented down the hall from Tyson's Bell Labs office—to their maximum potential. As the first Starlinks circled the planet, a construction crew in the Chilean Andes had just delivered the main mirror for what's now called the Vera C. Rubin Observatory, scheduled to open its shutters to the universe in the next couple of years. "All was happy and nice with our heads buried underneath the sand," Tyson says.

But Tyson and colleagues quickly apprehended the threat. In the lab, they simulated satellite streaks over the Rubin's Volkswagen-size, 3.2-gigapixel camera. Each photobombing satellite, the researchers found, would cause not just one useless streak of pixels, but a series of ghostly echoes. Yes, code could be written to avert the telescope's gaze when a satellite crossed over—but as the number of satellites in the sky ticked past 10,000 they would start to intrude into every exposure. The swarms would interfere not just with the Rubin, but any other wide-field studies of dark matter, dark energy, interstellar comets, and flaring transients such as supernovae. The satellites would also confound efforts to find potentially hazardous asteroids. Those searches need to be conducted around twilight—exactly when satellites are most visible.

Soon after the launches began, lawyers and activists got involved, asking pointed questions about whether near-Earth space—once the domain of nations and militaries, now open to businesses and billionaires—was an environmental commons in need of protection, like a forest or river. Executives such as Musk pushed back, arguing global broadband would be a boon for poor, isolated communities desperate for online opportunities. But Tyson, for the moment at least, wanted to avoid public conflict. He emailed a former contact at SpaceX, hoping to speak engineer-to-engineer as he would have in his Bell Labs days.

And so it was that Tyson and several colleagues found themselves on the phone with Musk himself, negotiating the first chapter in an ongoing environmental dispute over who exactly decides the future of the sky. According to other people on the call, Musk said that if astronomers were clever, they would just put their telescopes into space, where the seeing was better anyway. But doing that would cost 10 or 100 times more, the astronomers replied—and if SpaceX was clever, their engineers could just solve the satellite brightness problem cheaply.

Tyson, explaining the technical needs of the Rubin detector, pushed for dimming the satellites by a factor of 30 or even 100—with Musk balking at the latter figure. But at the end of the conversation, Musk turned to some SpaceX engineers on the call. "Fix this," he said.

**THE DREAM OF** satellite internet has come and gone before. In the 1990s, companies such as Globalstar and Iridium started to sell satellite phones that worked virtually anywhere on Earth, and Teledesic raised more than $1 billion for global satellite broadband. But one by one the companies went bankrupt, and by the time Teledesic shuttered, in 2002, its single prototype had burned up in the atmosphere.

More than a decade later, the cost of

building and lofting a satellite had fallen drastically—inspiring a spree of space internet schemes backed not just by billionaires, but also by the Chinese government. Unlike traditional internet satellites—large, expensive beacons perched in deep geostationary orbit—the satellites in these "constellations" would zip past at much lower altitudes. Many more satellites would be needed to ensure one was always above a given spot on the ground. But lower orbits would also mean shorter lag times, with signals whisking up and down in thousandths of a second—better for needs as diverse as online classes, emergency response, competitive video games, stock trading, and military communications.

On a Friday in January 2015, Musk stepped on stage at an invite-only gala in Seattle to announce Starlink's new headquarters, soon to open in nearby Redmond, Washington. There, engineers would re-create internet infrastructure from the top down. It was a first step, Musk said, toward a grander personal goal: making humanity a multiplanetary species. When someone asked how much the service would cost, he said it couldn't be free, because the goal was also to generate enough revenue to pay for a city on Mars.

Only one gatekeeper stood in Musk's way. Satellites need licenses from national agencies, such as the U.S. Federal Communications Commission (FCC), which regulate radio transmissions and coordinate internationally. That system governs the radio sky as a global commons, but imposes few other constraints. The FCC, for example, only requires that defunct satellites get out of low-Earth orbit within 25 years of a mission's end—through either natural or intentional deorbiting into the atmosphere, where they burn up.

Regulators do start to revoke licenses if a company doesn't deploy its approved satellites on schedule, however. Critics say the practice incentivizes corporations to follow a Silicon Valley–style, "fail fast, fail often" strategy. At Starlink, "There was a lot of talk about how, financially, we could possibly make this happen, and how the hell do you even launch that many things," a former team member says. "There was very little talk about it as a moral or ethical or even just a collision problem."

Those collision problems soon came into focus. In 2017, Hugh Lewis, an astronautics researcher at the University of Southampton, reported simulations showing that if even a small fraction of the satellites lost their ability to maneuver while in orbit, collision risks would soar, eventually causing hailstorms of new debris. To address those concerns, Starlink pushed its constellation below 600 kilometers, where spent satellites would fall out

# The gathering swarm

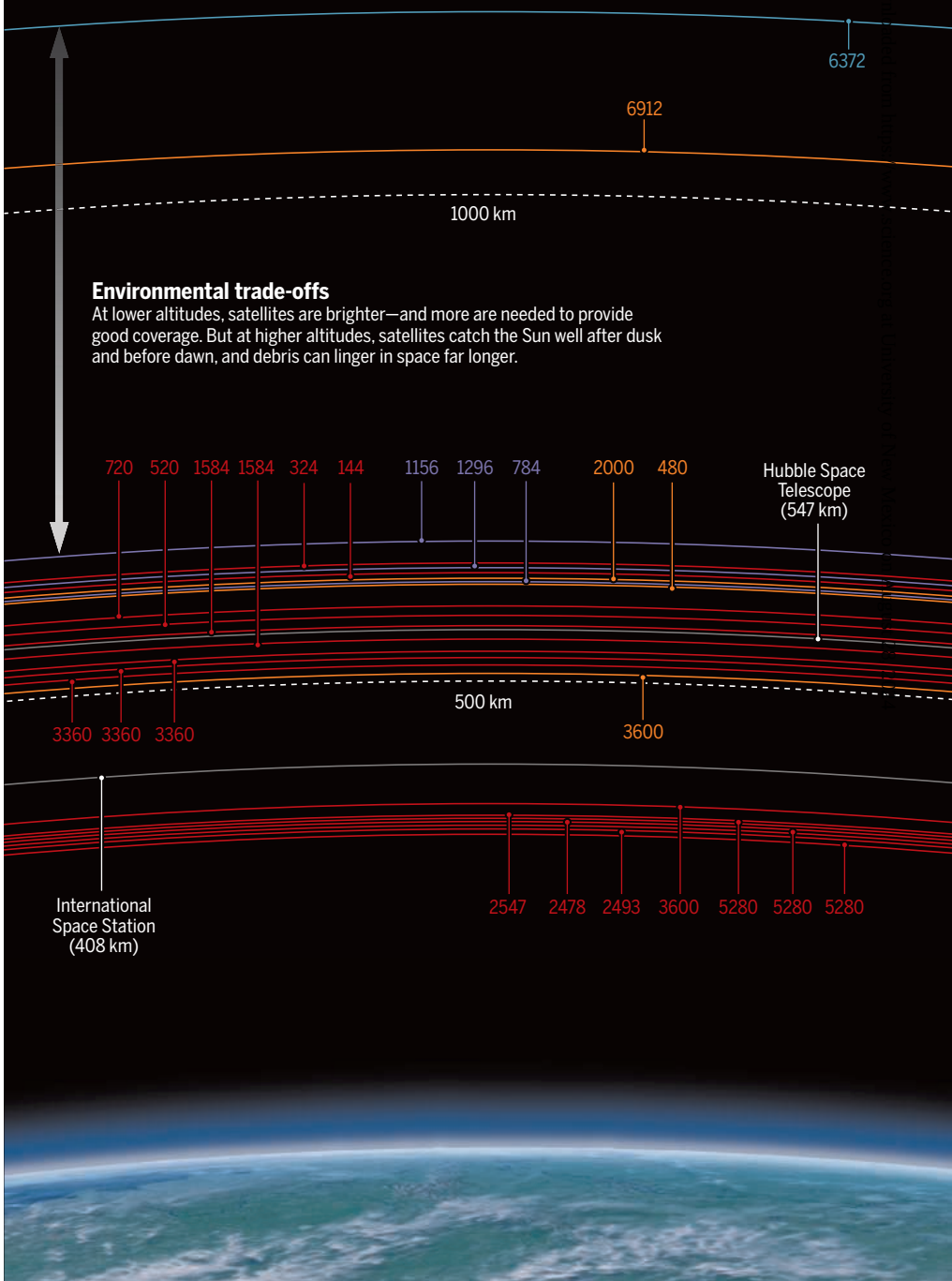
A slew of companies is planning to launch tens of thousands of internet satellites into low-Earth orbit, where they pose threats to astronomers and casual stargazers alike. Here's a 2D representation of what the four largest swarm builders have so far submitted to regulators. *Graphic by* **Chris Bickel**

**Starlink (41,914 satellites)**
The furthest along, Starlink internet service now reaches more than 90,000 users. Future satellites will be larger but designed from the start to limit visibility, the company says.

**OneWeb (6372 satellites)**
OneWeb satellites are fainter than Starlink's but are lit up by the Sun for more of the night. In 2020, the U.K. government and other investors bought the company out of bankruptcy.

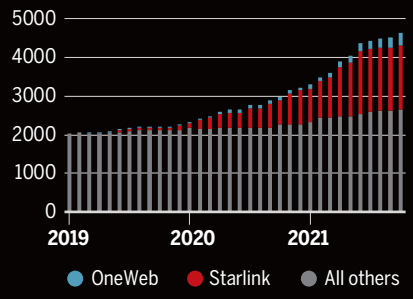
**China Star Network (12,992 satellites)**
In September 2020, China submitted plans to international regulators for a satellite broadband constellation. This year, a state-backed company was formed to develop it.

**Project Kuiper (3236 satellites)**
Amazon's project, headquartered a short drive from Starlink, says it will spend $10 billion to launch Kuiper in the 2020s using Atlas V rockets.



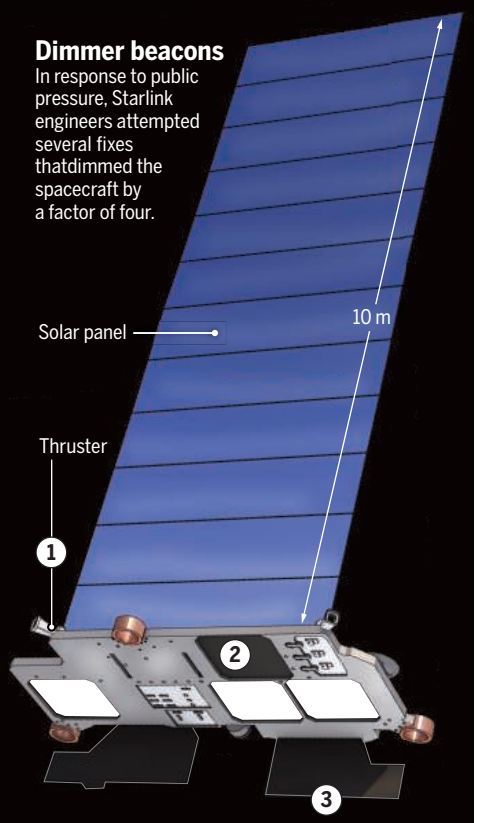
## Space race

In less than 3 years, Starlink and OneWeb have launched more than 2000 satellites. Those constellations represent more than 40% of all functioning satellites in orbit.




## Dimmer beacons

In response to public pressure, Starlink engineers attempted several fixes thatdimmed the spacecraft by a factor of four.




**1 Orbital maneuvers**
During the brightest period, days after launch, operators roll the satellite on its side to reduce reflections from the large solar panel. Once raised to operational orbit, the satellite's panel is angled like a shark fin to minimize glare.

**2 Dark coating**
Engineers tested painting underside surfaces black, but abandoned the practice.

**3 Sunshades**
The brightness of an operating satellite depends mainly on the flat antenna surfaces pointed down to Earth. Visors block some sunlight from ever hitting those surfaces.

DATA: JONATHAN MCDOWELL/HARVARD-SMITHSONIAN

of orbit quickly. But an accident there could still choke low-Earth orbit with dangerous debris for years afterward, Lewis says. "If you get it wrong, the space environment is not going to forget."

Few optical astronomers were paying attention to the looming threat. In the preceding century, they had coped with the glare of ever-brightening city lights by siting big telescopes on remote mountaintops. Light pollution had cost four-fifths of North Americans and one-third of the world their view of the Milky Way. But the problem was local, when it was a problem at all. Astronomers negotiated it with adjacent communities, not tech companies divvying up the planet's radio frequencies. "I don't read the FCC filings for entertainment purposes," Tyson says. "On balance, my bad."

**EVEN BEFORE MUSK'S EDICT** to fix the problem, SpaceX engineers had begun a collaboration with the Rubin group. "All they wanted from me at that point was one number," Tyson says. How much dimmer would the satellites have to get?

Astronomers measure brightness by using a system called apparent magnitudes, credited to the ancient Greek polymath Hipparchus, in which larger numbers correspond to fainter objects. The first Starlinks started out at about first or second magnitude, visible even from a city. As they settled into their long-term orbits, higher up, they faded to fourth or fifth magnitude, still visible from some suburbs. By contrast, a 15-second Rubin exposure could pick up distant galaxies at 24th magnitude, fainter by a factor of about 40 million.

Tyson and his team didn't ask for that much dimming. At seventh magnitude, Tyson says, the errant electronic signals caused by a Starlink pass over the Rubin would be manageable. And seventh magnitude mattered for another kind of detector, one with global implications, concluded an American Astronomical Society (AAS) committee on light pollution. "By gosh, that's the limit of human vision," Tyson says. "That's pure coincidence."

While the astronomers converged on that all-important number, Starlink engineers were at work. As sunlight falls on the planet, Earth casts into space a tapering shadow in the shape of a cone. Anything big flitting past the edge of that cone of night can scatter sunbeams down toward people or observatories already in darkness. And internet satellites, which broadcast powerful signals from flat, reflective radio antenna surfaces, tend to be large. The first Starlinks were especially bad, with 10-meter-long solar panels and off-white surfaces.

For a first test, Starlink engineers launched one satellite, painted with a less reflective coating. That darker surface dimmed the satellite, but also absorbed too much heat. In April 2020 they announced alternate tweaks. For the brightest period after launch, all the satellites would now roll on their sides to present a less reflective surface. Each satellite would also be built with a Sun visor, further cutting down on reflections.

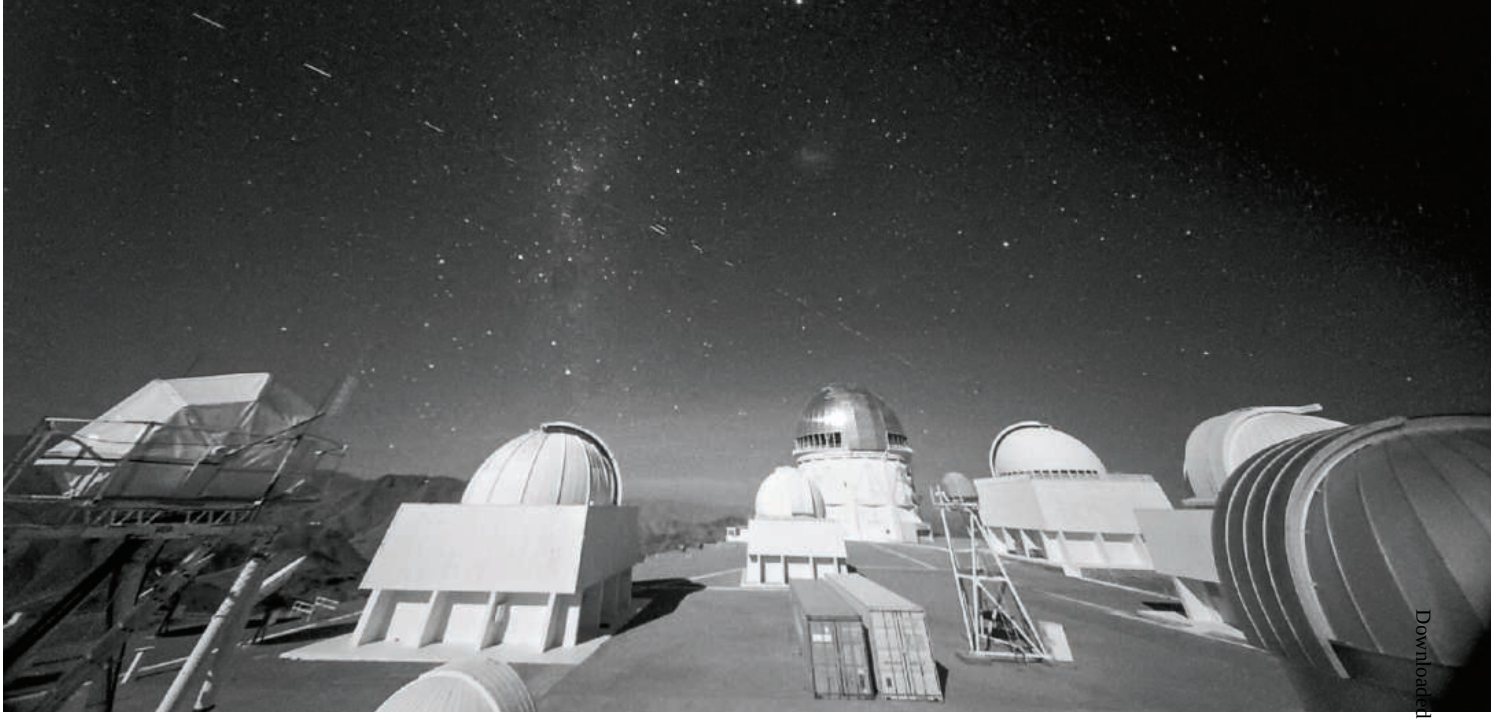
The visors helped. Of the nearly 1700 Starlinks now in orbit, more than 1000 have sunshades. Pat Seitzer, a member of AAS's light pollution committee, estimates that most appear between magnitude six or 6.5, not quite at the seventh-magnitude target, but about one-third to one-quarter as bright as the first Starlinks. "[SpaceX] really have set the standard," he says. Seitzer is relieved, although he says some astronomers and dark-sky advocates did not like the committee's decision to collaborate with SpaceX. "Several of us were compared to Neville Chamberlain, for having sold out the astronomical community."

Astronomers are still struggling to quantify how much the completed swarms will affect wide-field telescopes—assuming Starlink's competitors dim their satellites, too. Starlink's full flock might end up spoiling as little as 1% of Rubin data taken in twilight, and algorithms can scrub damaged pixels to remove some bright trails. But algorithmically corrected images could in turn bias studies of dark matter and dark energy—two unknown entities dominating the large-scale universe—that depend on measuring minute fluctuations across entire images. And Rubin astronomers worry even more that streaks and flashes from passing satellites might mimic the mysterious transient events Rubin was designed to discover: unanticipated flares lasting seconds or minutes.

"I don't mind my career being somewhat eaten by this," says Meredith Rawls, an astronomer at the University of Washington, Seattle, who has led efforts to mitigate satellites' effects on data. "But I would really love it if future astronomy grad students didn't have to have this rabbit hole."

The outlook worsens if future Starlinks trend brighter or if the other companies don't try to limit brightness. None has had comparable discussions with astronomers. "My hope was that it would be so obvious that it would shame all the other industries into complying," Tyson says of his work with Starlink. Lately, though, his hopes are fading. "You realize that it's really just the Wild West, and we astronomers are just a nuisance."

**WHILE ASTRONOMERS** worked to save their science, other factions began to voice a broader environmentalism: a sense of low-Earth orbit as a shared part of nature—and an unusually vulnerable one. There are no national or international laws to stop anyone



from launching an even lower, undimmed Starlink-size constellation, says Jonathan McDowell, an astronomer and space analyst at the Harvard-Smithsonian Center for Astrophysics. "My feeling now is a mix of relief that we were heard," McDowell says, "and nervousness that we are depending on the kindness of corporations."

One extant law might have teeth. In 2020, Ramon Ryan, a Vanderbilt University law student and former union organizer, read press coverage of the satellite light pollution issue and wondered whether opponents might have grounds to sue. He concluded they do, under the 1969 National Environmental Policy Act (NEPA). The law requires U.S. agencies to assess the environmental consequences of projects before approving them. Satellite licenses have been exempted since 1986 because they were assumed to have no environmental impacts—an assumption that could now be challenged.

The NEPA argument, published in a law school journal, surprised both SpaceX and astronomers. Outside lawyers bombarded AAS with offers to work on a case. But the organization's leadership declined, unsure whether it had the legal expertise and wanting to avoid a confrontation that could damage the SpaceX partnership.

Viasat, which operates geostationary internet satellites, was less skittish about challenging Starlink. In May, the company filed a petition in the U.S. Court of Appeals for the District of Columbia Circuit, arguing that the law requires the FCC to consider Starlink's environmental impacts on space debris and light pollution, but a decision is still pending.

The FCC has been successfully pressured to consider light pollution before, says Travis Longcore, an ecologist and light pollution researcher at UC Los Angeles—but it took a scrappy, grassroots campaign. In the early 2000s, conservation groups cited Longcore's research and leveraged NEPA to push the FCC to change how it regulated the height and illumination of communication towers that birds collide with. "[The FCC] had to get dragged kicking and screaming," he says.

Michelle Hanlon, a space lawyer at the University of Mississippi, says the Viasat lawsuit deserves a wider hearing. "It would be a shame for something this big to be decided by two private companies arguing before a judge." The NEPA debate turns on whether low-Earth orbit can be considered an extension of the human, earthly environment, she says. This summer, a panel of space lawyers—including Hanlon and lawyers from Amazon and SpaceX—considered the question. Even if space is not part of the human environment, they agreed, other U.S. laws—including those that recognize the importance of dark skies—serve as compelling reasons for the FCC to regulate constellation brightness.

Casual stargazers, dark-sky activists, and photographers also have a stake in the outcome, says Aparna Venkatesan, a cosmologist at the University of San Francisco. "Our constituents are humanity, not just professional astronomers," she says. An altered night sky would disproportionately impact Indigenous groups, she says, because it would damage spiritual and cultural practices involving the stars—traditions that have already suffered losses through policies such as residential boarding schools in the United States and Canada, which for decades aimed to assimilate Indigenous children far from home.

Hilding Neilson, an astronomer at the University of Toronto and a member of the Qalipu Mi'kmaq First Nation, thinks it's ironic that astronomers are speaking up for Indigenous cultures. For years, he notes, astronomers and Indigenous protesters in Hawaii have battled over building new telescopes on Mauna Kea, which Native Hawaiians consider a sacred mountain. But he agrees that large satellite constellations are a cultural threat and says launching them should require consent from sovereign groups down below. "If light pollution is erasing Indigenous stories, these satellites are rewriting them," Neilson says. "Did those nations get a choice?"

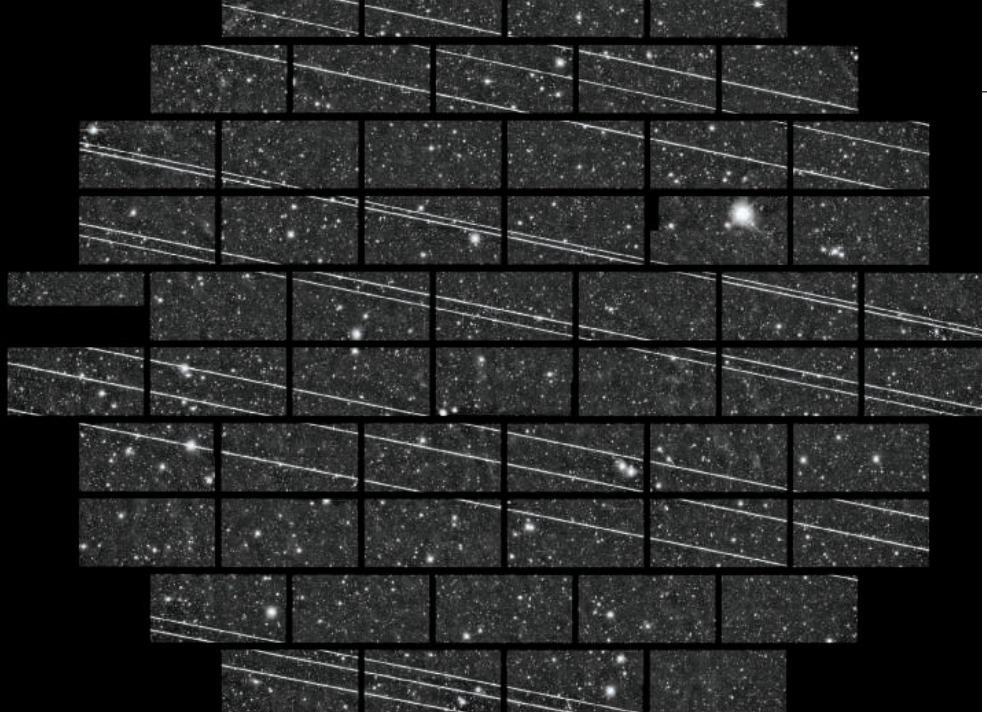
**SPACEX EXECUTIVES**, responding to those criticisms, have pointed to their own efforts to bring Starlink service to rural Indigenous communities. On a Wednesday morning in June, I visited one on Washington's Olympic Peninsula.

At a checkpoint in front of the Hoh Reservation, I met Melvinjohn Ashue, the tribe's economic development officer, who was wearing a Baltimore Ravens hat. I held out my wrist for a temperature check and confirmed I had no COVID-19 symptoms.

Then we drove in separate cars past moss-blanketed trees and into a small neighborhood of modest single-story houses, each with a white Starlink dish the size of a small pizza gleaming down from slanted roofs. Ashue said he had helped mount them, weighting them down with cinder blocks against the area's battering storms.

At the pandemic's beginning, 15 of the tiny reservation's 28 homes were still on a waiting list for internet service. When school went online, the district equipped families with mobile hot spots, but cell service is also spotty. Ceciliajean Ashue, Melvinjohn's sister, said she was missing online seminars at work

PHOTO: CTIO/NOIRLAB/NSF/AURA



In November 2019, a Starlink satellite train was visible over Cerro Tololo in Chile (left). It left streaks on the Blanco telescope's wide-field camera (right).

PHOTO: CTIO/NOIRLAB/NSF/AURA/DECAM DELVE SURVEY

while trying to juggle the class schedules of three school-age children—only one of whom could go online at a time.

Just then Starlink was searching for a pilot community at the right latitude. The Washington Statewide Broadband Office suggested the Hoh, relegated to the far northwest corner of the state by an 1855 land-grabbing treaty. In September 2020, Starlink team members arrived to help set up the dishes, making the tribe among the first people outside SpaceX to get a glimpse of the service. Today, Melvinjohn Ashue says, the tribe has a 3-year deal to buy Starlink terminals and subscriptions—services that retail for $500 for the dish and $99 monthly payments. Eventually, he adds, the Hoh hope to switch from Starlink to a ground-based fiber connection, one that would let the tribe be its own internet service provider—and perhaps reap some of the federal incentive money that went to Starlink for offering rural broadband access.

Connectivity through Starlink has helped with education and a vaccine clinic and allows ceremonies to be livestreamed. Coverage drops out when it rains but quickly returns. And the satellites themselves may have even inspired careers in aerospace. "At night, my kids like to watch for the blinking lights," Ceciliajean Ashue says. "We get the Navy flying over us constantly. A satellite going by doesn't bug us as much."

Juan-Carlos Chavez, a Seattle-based information scientist affiliated with the Yaqui tribe of the Sonoran desert, is more concerned. "Telehealth, tele-education, we need that too," says Chavez, who advises Pacific Northwest tribes on securing broadband access. "But deploying a bunch of satellites up there to quote-unquote solve the problem is something that we really gotta consult communities with."

Later in the summer, in the state's northeast corner, Chavez waited for wildfire smoke to clear and the stars to rise over his campsite at Colville National Forest. As he concentrated that evening, gazing up to connect with the grandfather who first taught him to seek wisdom from his elders in the stars, a moving dot crossed by. "When you're in deep ceremony and you see something moving that's not supposed to be there, it detracts from being in the place of harmony with your elders and ancestors," Chavez says.

**LAWS MAY NOT** protect that view, but diplomats can change norms on the international stage. "There's no enforcement, but there is that sort of 'name and shame,'" Hanlon says. "That carries weight."

The International Astronomical Union (IAU) has long prodded UNESCO to declare the night sky a protected World Heritage Site, to no avail. But in 2017, international astronomers approached a different U.N. committee in Vienna that might have more jurisdiction over the sky—the Committee on the Peaceful Uses of Outer Space (COPUOS).

Three years later, a group of astronomers, satellite engineers, and other experts gathered by IAU submitted their final report to COPUOS summarizing threats to the night sky: ground-based light pollution, radio interference, and then satellites, an issue they hadn't even anticipated when they started. The report recommends satellite constellations orbit below 600 kilometers—a tradeoff that makes them visible only around twilight for much of the year, but brighter when they are visible—and that they never outshine seventh magnitude, the original threshold Tyson negotiated.

Astronomers hope COPUOS will pass the recommendations to the U.N. General Assembly and that they will spur diplomats to acknowledge the importance of dark, quiet skies. But building consensus takes time. "It's even slower than you might think it would be," says Connie Walker, an astronomer at NSF's National Optical-Infrared Astronomy Research Laboratory, who helped present the report.

Timiebi Aganaba, a space governance expert at Arizona State University, Tempe, predicts such developments will eventually shift space from an inaccessible, specialized domain to a shared one, governed by laws and norms. "These are age-old problems," she says. "Space is not that unique—it's just another domain of human activity now."

For now, the future is uncertain. Before leaving Washington in June, I drove to the center of the state and then rattled down several gravel and dirt roads toward a bare lot with a sign out front: Goldendale Sky Village.

In the past 3 years, a neurosurgeon named Christopher Smythies has persuaded 46 professionals from Seattle and Portland, Oregon—lawyers, accountants, firefighters—with a shared loved of amateur astronomy to buy into a limited liability company that lets them set up camp here, under skies that are darker than the surrounding areas and almost the entire eastern United States.

True to Seattle stereotype, my entire week in Washington had been cloudy. This night's forecast was little better, but a smattering of hobbyists had come out in recreational vehicles anyway, for the company and fresh air. Smythies says he was here in May 2019, when the first string of 60 Starlink satellites blazed across the sky. "We thought we were being invaded by space aliens or something," he says. "It's not a problem for us right now, but if they put up tens of thousands of satellites it'll become one." Meanwhile the village has grown—and gained an internet connection through a Starlink dish.

As the clock ticked past 10 p.m., then 11 p.m., and clouds still obscured the sky, I set off for a motel and stopped at a remote, unlit intersection a few minutes away. Head craning up, I watched the Big Dipper and a spill of fainter stars finally peek from a gap. And within 1 minute the dim speck of a satellite traced a line through the clearing, sliding across the constellation, until it, too, passed behind the clouds. ■

Joshua Sokol's journalism on the night sky is supported by the Alicia Patterson Foundation.